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A review of wind energy technologies

G.M. Joselin Herbert[a], S. Iniyan[b,*], E. Sreevalsan[c], S. Rajapandian[d]

[a]*Department of Mechanical Engineering, St. Joseph's College of Engineering, Chennai-119, India*
[b]*Department of Mechanical Engineering, Anna University, Chennai-25, India*
[c]*Center for Wind Energy Technology (C-WET), Chennai 601-302, India*
[d]*Electrical Department, Sathyabama Institute of Science and Technology, Chennai-119, India*

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Abstract

Energy is an essential ingredient of socio-economic development and economic growth. Renewable energy sources like wind energy is indigenous and can help in reducing the dependency on fossil fuels. Wind is the indirect form of solar energy and is always being replenished by the sun. Wind is caused by differential heating of the earth's surface by the sun. It has been estimated that roughly 10 million MW of energy are continuously available in the earth's wind. Wind energy provides a variable and environmental friendly option and national energy security at a time when decreasing global reserves of fossil fuels threatens the long-term sustainability of global economy. This paper reviews the wind resources assessment models, site selection models and aerodynamic models including wake effect. The different existing performance and reliability evaluation models, various problems related to wind turbine components (blade, gearbox, generator and transformer) and grid for wind energy system have been discussed. This paper also reviews different techniques and loads for design, control systems and economics of wind energy conversion system.

Keywords: Wind power technology; Reliability evaluation model; Aerodynamic model; Wind resource assessment

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*Corresponding author. Tel.: +91 44 235 1723.
E-mail address: iniyan777@hotmail.com (S. Iniyan).

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1. Introduction

The wind turbine technology has a unique technical identity and unique demands in terms of the methods used for design. Remarkable advances in the wind power design have been achieved due to modern technological developments. Since 1980, advances in aerodynamics, structural dynamics, and "micrometeorology" have contributed to a 5% annual increase in the energy yield of the turbines. Current research techniques are producing stronger, lighter and more efficient blades for the turbines. The annual energy output for turbine has increased enormously and the weights of the turbine and the noise they emit have been halved over the last few years. We can generate more power from wind energy by establishment of more number of wind monitoring stations, selection of wind farm site with suitable wind electric generator, improved maintenance procedure of wind turbine to increase the machine availability, use of high capacity machine, low wind regime turbine, higher tower height, wider swept area of the rotor blade, better aero-dynamic and structural design, faster computer-based machining technique, increasing power factor and better policies from Government.

Even among other applications of renewable energy technologies, power generation through wind has an edge because of its technological maturity, good infrastructure and relative cost competitiveness. Wind energy is expected to play an increasingly important role in the future national energy scene [1,2]. Wind turbines convert the kinetic energy of the wind to electrical energy by rotating the blades. Greenpeace states that about 10% electricity can be supplied by the wind by the year 2020. At good windy sites, it is already competitive with that of traditional fossil fuel generation technologies. With this improved technology and superior economics, experts predict wind power would capture 5% of the

world energy market by the year 2020. Advanced wind turbine must be more efficient, more robust and less costly than current turbines. Ministry of Non-conventional Energy Sources (MNES), Indian Renewable Energy Development Agency (IREDA) and the wind industry are working together to accomplish these improvements through various research and development programs. This article gives a brief overview of various wind turbine technologies.

2. World wind energy scenario

The technical potential of onshore wind energy is very large—$20{,}000 \times 10^9$–$50{,}000 \times 10^9$ kWh per year against the current total annual world electricity consumption of about $15{,}000 \times 10^9$ kWh. The economic potential depends upon factors like average wind speed, statistical wind speed distribution, turbulence intensities and the cost of wind turbine systems. The Global Wind Energy Council is the global forum for the wind energy sector, uniting the wind industry and its representative associations. The members operate in more than 50 countries and represent over 1500 organizations involved in hardware manufacturer, project development, power generation, finance and consultancy, as well as researchers and academics.

The global wind power industry installed 6614 MW in the year 2004, an increase in total installed generating capacity of nearly 20%. The cumulative global wind power capacity has grown to 46,048 MW. The countries with the highest total installed wind power capacity are Germany 16,500 MW, Spain 8000 MW, The United States 6800 MW, Denmark 3121 MW and India 2800 MW. The top five countries account for nearly 80% of total wind energy installation worldwide. A number of countries, including Italy, the Netherlands, Japan and the UK, are above near the 1000 MW mark. The detailed operating wind power capacity for different countries are shown in Table 1.

Europe continued to dominate the global market in 2004, accounting for 73% of new installations, 4825 MW. Asia had a 12.4% share 822 MW and the Pacific Region 4.4%, 291 MW, Middle East Africa 1.1%, 71 MW followed by Latin America 0.64%, 42 MW.

2.1. Wind turbine sizes

In the early and mid-1980s, the typical wind turbine size was less than 100 kW. By the late 1980s and early 1990s, turbine sizes had increased from 100 to 500 kW. Further, in the mid-1990s, the typical size ranged from 750 to 1000 kW. And by the late 1990s, the turbine size had gone up to 2500 kW. Now turbines are available with capacities up to 3500 kW.

2.2. Wind power in selected countries

Till the early 1980s, the Unites States possessed 95% of the world's installed capacity. In the early 1980s, combined Federal and State investment tax credits amounted to 50–55% of the investment. In United States, the cost of wind-generated electricity has fallen from 35¢/kWh in the mid-1980s to 4¢/kWh at prime wind sites in 2001. In United States, wind-generating capacity is growing by leaps and bounds. The 300 MW Stateline Wind Project under construction on the border between Oregon and Washington will be the world's largest wind farm.

Table 1
Operating wind power capacity in MW

Europe	Start 2004	End 2004	USA	Start 2004	End 2004	Pacific Region	Start 2004	End 2004
Germany	14,609	16,500	California	2016	2045	Japan	644	740
Spain	6202	8000	Texas	1305	1396	Australia	198	252
Denmark	3115	3121	Lowa	472	632	New Zealand	38	168
Netherlands	912	1077	Minnesota	562	577	Pacific Island	0	11
Italy	891	1020	Wyoming	284	284	**Total**	**880**	**1171**
UK	704	944	New Mexico	206	266	Asia		
Austria	415	585	Oregon	261	261	India	2120	2800
Sweden	399	428	Washington	244	244	China	566	700
Portugal	299	409	Colorado	223	229	Taiwan	8	16
Greece	398	398	Oklahoma	176	176	South Korea	8	8
France	240	390	Pennsylvania	128	129	Sri Lanka	3	3
Ireland	225	256	Kansas	113	113	**Total**	**2705**	**3527**
Norway	112	160	Illinois	50	105	Middle East & Africa		
Finland	47	82	North Dakota	66	66	Egypt	69	140
Belgium	68	68	West Virginia	66	66	Morocco	54	54
Poland	58	58	Wisconsin	53	53	Tunisia	20	20
Ukraine	51	57	New York	49	49	Iran	11	11
Latvia	24	24	South Dakota	44	44	Israel	8	8
Luxembourg	16	24	Tennessee	2	29	Cape Verde	3	3
Turkey	20	20	Nebraska	15	15	South Africa	3	3
Czech Republic	10	10	Ohio	4	8	Jordan	2	2
Russia	7	7	Vermont	6	6	**Total**	**170**	**241**
Switzerland	5	8	Michigan	3	3	Latin America		
Hungary	2	6	Hawaii	2	2	Costa Rica	71	71
Estonia	5	5	Alaska	1	1	Caribbean	13	55
Slovakia	0	2	Massachusetts	1	1	Brazil	29	29
Romania	1	1	**Total**	**6352**	**6800**	Argentina	26	26
Total	**28,835**	**33,660**	Canada	326	441	Columbia	20	20
World total wind power capacity is 46,048 MW						Mexico	5	5
						Chile	2	2
						Total	**166**	**208**

Source: Wind power monthly, January 2005.

Europe is the global leader in wind energy, and witnessing the globalization of the wind energy markets. In Europe, the market has experienced average annual growth rates of 22% over the past 6 years. The European Wind Energy Association has recently revised its 2010 wind capacity projections for Europe from 4×10^4 MW to 6×10^4 MW.

In Europe, offshore projects are now springing up off the coasts of Belgium, Denmark, France, Germany, Ireland, Netherlands, Scotland, Sweden and United Kingdom. Once a country has developed 100 MW of wind-generating capacity, it tends to move quickly to develop its wind resources. The United States crossed this threshold in 1983. In Denmark, this occurred in 1987. In Germany, it was 1991, followed by India in 1994 and Spain in 1995.

Germany has made impressive gains in installed wind capacity since 1991, and is now setting the trend for Europe's future. In mid-1997, Germany surpassed the US as the country with the largest wind capacity. There is 1891 MW capacity increase in 2004, while the installed capacity at end 2004 is 16,500 MW.

Denmark ranks as the world's largest manufacturer and exporter of wind turbines and it has the third largest capacity in the world. Almost 60% of the world's wind turbines are manufactured in Denmark. The Danish government has set substantial targets for growth in wind-powered electricity generation and expects it to account for 50% of domestic generation by 2030.

Spain has seen substantial growth in wind power capacity in the past several years. The current capacity stands at 8000 MW. The government encourages the development by offering producers a choice of incentives. Australia has some of the most powerful and abundant untapped wind resources on the planet and a grid capacity that can potentially accommodate up to 8000 MW of wind energy with minor adjustments.

The year 2004 was a record year for the Canadian wind energy industry with 116 MW of new installed capacity. Recent developments in Federal and Provincial energy policy promise a 10-fold increase in Canada's total installed wind energy capacity over the next 5 years said CanWEA (Canadian Wind Energy Association) President Robert Hournung. India ranks fifth in installed wind capacity. India has witnessed unprecedented growth in the wind energy sector. During the last fiscal year, i.e. 2003–2004, wind energy capacity in India grew by more than 35%. Japan plans to attain the wind power target of 3000 MW by the year 2010 after the Kyoto Protocol. It has installed about 740 MW to date, which is 20 times in comparison to 5 years ago and one third of the national target [3].

2.3. Future wind power development

Under the international agreements on Environment commitments scenario, the penetration is expected to be faster and the 10% level is achieved by the year 2016. The expected saturation level capacity is 1.9×10^9 kW occurring at 2030–35.

3. Wind resource assessment

The study of geographical distribution of wind speeds, characteristic parameters of the wind, topography and local wind flow and measurement of the wind speed are very essential in wind resource assessment for successful application of wind turbines. A brief review of these assessment techniques have been reviewed in this literature.

Kocak was concerned with speed persistence, which is an important factor in maintaining wind energy production [4]. Wood determined the optimum tower height using power law and by algorithmic law. The optimum height increases as the wind shear increases for village and suburban terrain [5]. The site with annual mean wind speed of 20 km/h with a hub height of 30 m and power density of 150 W/m^2 is economically viable annual wind speed for power generations. The Weibull density function had been used by Weisser for the analysis of wind energy potential of Grenada (West Indies) based on historic recordings of mean hourly wind velocity [6]. Panda et al. made a stochastic analysis of the wind energy potential at seven representative weather stations in India. A probability model for the wind data and potential has been developed. They used Box–Cox transformation to transform the data for all of the stations to a normal distribution [7].

Lambert et al. described full-scale instrumentation and analysis of tall-guyed lattice masts to correlate wind speed and direction with structural stresses, particularly in welds [8].

Sami et al. proposed a probabilistic model to assess the energy resources available from wind energy conversion systems at two sites, which enables the representation of equipment failure modes and the intermittent nature of the wind resource [9]. Jamil et al. used Weibull probability distribution function to find out the wind energy density and other wind characteristics with the help of the statistical data of 50 days wind speed measurements the Materials and Energy Research Centre (MERC)-solar site, Tehran in Iran [10]. A Cumulative Semi-Varigram (CSV) model had been derived by Zekai Sen and Ahmet D. Sahin to assess the regional patterns of wind energy potential along the western Aegean Sea coastal part of Turkey. This innovative technique provides clues about regional variations along any direction. The CSV technique yielded the radius of influence for wind velocity and Weibull distribution parameters. The dimensionless standard regional dependence (SRD) functions are obtained from the sample CSV, which has been used to make simple regional predictions for the wind energy or wind velocity distribution parameters [11]. Youcef Ettoumi et al. used first-order Markov chain and Weibull distribution methods for statistical bivariate modeling of wind using the data wind speed and wind direction measurements collected every 3 h at the meteorological station of Essenia (Oran, a state in Algeria). Also, a detailed study has been made on the statistical features of the wind at Oran [12]. Torre et al. proposed Markovian model for studying wind speed time series in Corsica because a stochastic model like a Markov chain seems to be more accurate [13]. Feijoo et al. suggested two methods for assessing the effect of multiple wind turbines on a large power system based on Monte Carlo wind speed simulation of different wind farms where measurements of average values and correlation are included [14]. Ulgen et al. studied the wind variation for a typical site using Weibull distribution and Rayleigh distribution was found to be suitable to represent the actual probability of wind speed data for the site studied [15]. The detailed description of the various types of equipments, instruments, site specifications and other technical needs for the wind assessment project in Saudi Arabia had been presented by Alawaji [16]. Emeis measured 10 min average wind speed using mini sodar at different sites in Germany. He also discussed implications for the siting of wind turbines [17].

A comparison work on various forecasting techniques applied to mean hourly wind speed was done by Sfetsos using time series analysis, traditional linear models, feed forward and recurrent neural networks, Adaptive Neurofuzzy Interference Systems (ANFIS) and neural logic network [18]. The mean hourly wind speed data-forecasting model using time series analysis has been presented by Sfetses [19]. Poggi et al. have discussed an autoregressive time series model for forecasting and simulating wind speed in Corsica [20]. Aksoy et al. had presented synthetic data generation techniques, which were used in practice for cares where long wind speed data were required. In this study, a new wind speed data generation scheme based upon wavelet transformation is introduced and compared to the existing wind speed generation methods [21]. Cyclone hit in Gujarat in 1998 still proves beyond doubt the inadequacy of past assessment. An Indian Type Certification system, type approval provisional scheme (TAPS 2000), established with the International Electro-technical Commission (IEC) had been mentioned by Prasad et al. [22]. Prasad had presented an over view of the certification systems and issues related to the assessment of the suitability of the wind turbine [23]. Cermak had explained research and experience resulting from wind-engineering practice had shown that some

wind-environment properties had significantly more effects or influence on the various receptors [24].

4. Site selection

Wind availability, influence of height of installation above ground, effect of wind gusting and micro-siting of WEGs are the main influences of annual energy output. These factors and different models have been reviewed in this literature in a brief manner.

Berkhuizen et al. had described various siting procedures for large wind energy projects [25]. Murakami et al. had suggested meteorological model and wind engineering model for selecting a suitable site for windmill construction [26]. Rajesh Karki et al. had presented a simulation method to help system planners decided on appropriate installation sites, operating policies, and selection of energy types, sizes and mixes in capacity expansion when utilizing PV and wind energy in small isolated systems [27]. Thomsen et al. had compared potentials for site-specific design of MW sized wind turbines installed at different sites. The results showed that the variation in aerodynamically driven loads and energy production could be more than 50% between the different sites [28]. Peter Fuglsang et al. had presented a method for site-specific design of wind turbines and compared a 1.5 MW stall regulated wind turbine in normal onshore flat terrain and in offshore wind farm and showed a potential increase in energy production of 28% and installation cost reduced by 10.6–4.6% for the offshore wind farm [29].

Mertens described the flow features and guidelines for siting of small wind turbines on the roof [30]. Bowen had discussed some relevant issues concerning the wind tunnel modeling of wind flows over complex terrain during naturally stable, strong wind episodes [31]. Peng et al. had presented a time sequential simulation technique to evaluate the reliability of a distribution system including WTG as an alternative supply. The effects on the system reliability benefits of the wind site selection and the number of wind units are investigated [32]. Availability of wind energy and its characteristics at Kumta and Sirsi in Uttar Kanada district of Karnataka had been studied by Ramachandra et al., based on primary data collected at these sites for a period of 24 months [33]. Using a given type of wind electric generator and from official meteorological data Ramachandra et al. secured maximum output of power. The analysis showed that coastal and dry arid zones have good wind potential [34].

5. Wind turbine aerodynamics

Aerodynamics is a science and study of physical laws of the behavior of objects in airflow and the forces that are produced by airflows. There are significant interactions with universities, industries and foreign researchers in the area of fundamental aerodynamics. Different models of aerodynamic analysis of wind turbine system have been reviewed in this paper.

Miller had made aerodynamics and dynamic analysis of horizontal axis wind turbines and also highlighted the need for a comprehensive design theory. The unsteady aerodynamic loads resulting from wind shear may be estimated from relatively simple momentum theory [35]. Karl et al. had examined the modal behavior teetered-rotor turbine using simple models, ranging from one to seven degrees-of-freedom and showed that the governing equations are periodic and that a Floquet analysis must be used to

correctly predict the modal behavior, in particular the damping and therefore stability [36]. Christian et al. studied modification of the NACA 62_2-415 leading for better aerodynamic performance and suggested several causes for double stall [37]. Horizontal axis wind turbines are extremely dynamic structures, which are subject to complex distributions of aerodynamic loading. Malcolm studied inflow with vertical wind shear showed strong 3P participation of mode #3. This illustrates how strong vertical wind shear can lead to motion not only in the vertical plane but also to a yaw motion of the rotor [38].

Idriss Ammara et al. had suggested a viscous three-dimensional differential/actuator-disk method for the aerodynamic analysis of wind farms. The inefficient spacing between the turbines reduced the performance associated with the wake effect [39]. Schreck and Robinson had analyzed rotational augmentation of horizontal axis wind turbine blade aerodynamics response and concluded that rotational augmentation was associated with chord- and span-wise pressure signature [40]. Xabier et al. presented results from a wind tunnel-based examination of the response of a wind turbine blade to tower shadow in head on flow. It had been shown that the blade response to tower shadow is not symmetric about the center of the tower shadow region [41].

Mayda et al. analyzed the NREL S809 airfoil for stall-controlled horizontal-axis wind turbines at a chord Reynolds number of 1.0×10^6. For all flow conditions involving laminar separation, bubble-induced vortex shedding was observed. This flow phenomenon causes significant oscillations in the airfoil surface pressure and, hence, in the airfoil-generated aerodynamic forces [42]. Honer et al. concentrated vorticity shed from both sides of the tower could produce a blade vortex interaction-type effect [43]. Schreck et al. had studied the Blade Dynamic Stall vortex kinematics for three-dimensional, unsteady, vortex dominated flows occurring on horizontal axis wind turbine blades at different wind speeds and various yaw angles [44]. Fleig et al. had investigated the physical mechanisms associated with broadband tip vertex noise caused by rotating wind turbines using compressible large-eddy simulation and direct noise simulation [45]. Brooks and Marcolini experimentally investigated tip vortex noise formation. They found that for the stationary blades, tip vortex noise is of lesser importance to the overall broad band self-noise spectrum than boundary layer and trailing edge noise [46]. Losslein had said for designing a wind load concept, it is essential to have some information concerning the size of eddies during strong winds. To get statistical information of these data, long-term measurements were needed on the occasion of strong winds [47]. Sutherland used the long-term data set from the LIST program to examine the structural response of the Micon wind turbine to the inflow conditions and analyzed the structural and inflow data and illustrated that the vertical component of the inflow was the most important of the secondary inflow parameters with respect to fatigue loads [48]. Schreck et al. tested a wind turbine and normal face and flow field topology information were obtained from measured surface pressure to disclose the effects of varying tip speed ratio on rotational augmentation and concluded after shear layer impingement commences higher tip speeds generally produce normal forces [49].

Different types of aerodynamic noise can be distinguished notably low frequency noise, inflow turbulence noise and airfoil self-noise as described in Burton et al. [50]. Fox and Tony had investigated and presented the details of the wind effects on perpendicular structural intersections composed of either two circular cylinders or two square-section bars. The investigation revealed that the wind effects are dependent upon section type, and whether the members intersect in a single plane or fixed one behind the other with a point

of contact [51]. A theoretical analysis was performed by Banks and Gadd for steady laminar boundary layers on a rotating blade [52]. Madsen and Christensen conducted experiment and concluded rotational effects to be of minor importance compared to the influence of aspect ratio and span-wise pressure gradient [53]. Bet and Grassmann discussed a model of a wind turbine with a wing-profiled ring around it and presented various fluido dynamical calculations in order to study the resulting increase in power. The result showed increase in the power of a wind turbine by a factor of 2.0 by means of a wing structure [54]. Deyuan et al. analyzed a load spectrum and fatigue life of the blade of horizontal axis wind turbine using the finite element model superposition method, the distributions of aerodynamic loads using the strip theory and the influences of stiffening effect and material anisotropy on the blade vibration modes [55].

5.1. Wake effect

To determine how the lift of an aerofoil actually developed it is essential to study the wake effect. The different wake effects have been reviewed in this paper.

Hassan et al. had drawn attention to the importance of dynamic loading effects of the operation of a wind turbine in the wake of another. Analysis of the limited data presented here suggested an increase of extreme loads of about 50% and an increase in fatigue damage rate of 17% [56]. Ken Chaney et al. had used the dynamic inflow, Coleman models and YawDyn model for accurate prediction of both the center of thrust location and the magnitude of the thrust on a rotor disk [57]. Zerovos et al. had developed a numerical method for the computation of wakes structure and development of horizontal axis wind turbines [58]. Ainslie had described a numerical model to calculate the flow field in the wake of wind turbine [59]. Wake affected wind speed profiles at Vindeby offshore windfarm have been compared by Schlez et al. with the model for single, double and quintuple wakes cases [60]. In April 2001 Folkerts et al. conducted the first offshore wake measurement with sonic detection and ranging (SODAR) at Vindeby and wake effects were measured at 1.4 and 7.1 time the rotor diameter distance between turbines and found velocity deficits varying from 12% to 56% [61]. Rabecca et al. had performed six wake models to evaluate the performance of offshore windfarm due to wake. One of the wake models is being coupled with a full aeroelastic model for the calculation of wind loads on the turbines [62]. Rados et al. had compared six wake models to evaluate the performance of wake models in order to ascertain the improvements required to enhance the prediction of power output with the large offshore wind farm [63].

6. Performance and reliability of wind turbines

Researchers and scientists had developed various models for the evaluation of performance of wind turbine system. A brief review of these models has been presented here.

Abderrazzag had investigated the performance and energy production of a grid connected wind farm during 6 years operation and illustrated the variation in energy and wind speed on an annual and monthly basis for the whole examined period [64]. Saramourtsis et al. presented a probabilistic method used for the evaluation of the performance and reliability of wind-diesel energy systems [65]. Castro Sayas and Allan built a probabilistic model of a wind frame taking into account the stochastic nature of the

wind, the failure and repair processes of wind turbines, and the spatial wind-speed correlation and wake effects [66]. Dokopoulos et al. proposed a Monte Carlo-based method for predicting the economic performance and reliability of autonomous energy systems consisting of diesel generators and wind energy converters (WECs) [67]. Abouzahr and Ramkumar studied the performance of an autonomous WECS composed of one wind turbine feeding the load via a battery storage [68].

Billinton and Guung bai conducted studies on generating capacity adequacy associated with wind energy, using a sequential Monte-Carlo simulation procedure. The result shows that the contribution of WECs to the reliability performance of a generating system is highly dependent on the site wind condition [69]. A sequential Monte-Carlo simulation technique based on an hourly random simulation had been proposed by Billinton et al. for adequacy evaluation of a generating system including WECS [70]. Bhatt et al. studied prediction and enhancement of performance of wind farm in India and found that there is scope for improvement in the annual plant load factor by 1–3% by improving the grid and machine availability [71].

Feasibility studies of horizontal and vertical axis of wind turbine of floating offshore windfarm in Japanese water had been done by Vahiyma et al. It is realized that horizontal axis machines are now dominants [72]. Bowen reviewed the growing demand for less conservative and therefore more economic structural designs has produced a strong need for improved accuracy in the prediction of wind loadings [73]. An advanced model based on recurrent high-order neural networks, is developed by Kariniotakis et al. for the prediction of the power output profile of a wind park [74]. Holcher had explained new storm regulation software, it helps to stabilize the grid during a storm wind and permits additional energy yield. The converter itself is subjected to less stress, because the switch off and start up process at high wind velocities are avoided, along with their associated load peaks [75]. Wan et al. presented statistical properties of the data collected and discussed the results of data analysis to evaluate short-term wind power fluctuations and their impact on electric power systems [76]. Shuhui et al. examined and compared regression and artificial neural network models used for the estimation of wind turbine power curves [77].

A detailed parametric analysis such as available wind potential quality, examination of wind power curve, investigation of reliability for determining minimum cost is carried out concerning the optimum sizing of stand-alone wind power system by Kaldellis resulted in an appropriate decision making procedure, a significant reduction of the system dimensions may be realized leading to a remarkably diminished first installation cost [78]. Kelouwani et al. studied nonlinear identification of wind turbine with a neural network, and found that variable speed wind turbine can produce 8–15% more energy output as compared to their constant speed counter parts [79]. Wilson studied the various losses such as aerodynamic, mechanical, electrical, transmission and generator losses that reduce the power output. In that transmission and generator losses are of the order of 12% at rated power. The rotor performance is depending on the action of lift and drag forces on the blades [80].

Caselitz et al. during installation of WEGs in autonomous systems, technical constraints must be considered, since increasing wind penetration may disturb the operation of the system, leading to oscillation of voltage and frequency. Also in cases of high wind speeds the outage of WECs may damage conventional units [81]. In order to improve the effectiveness and efficiency of research into wind energy conversion systems Noval wind

turbine simulators had been developed by Housin et al. to create a controlled test environment for drive train of wind turbine [82].

Camporeale et al. presented an innovative electronic system for testing the performance of wind turbines. The main goal of the system is to increase the accuracy in the measurements of torque and speed for each steady-state point of the turbine characteristic power curve [83]. The steps to be adopted by the government agencies in order to ensure the desired growth of the wind industry in the country had been suggested by Skiha et al. and listed the suggestion to meet the technical challenges faced by the wind industry and to improve the performance of wind farms and also suggested a right choice of wind electric generator with an optimum rated wind speed will improve the wind farm performance [84].

6.1. Reliability

Reliability of wind turbine system is based on the performance of its components under assigned environment, manufacturing process, handling, and the stress and aging process.

Bakirtz developed a probabilistic technique to evaluate the reliability of an autonomous system [85]. Singh and Lago-Gonzalez used chronological simulation to model nondispatchable sources at each hour as multistate units, which are then convoluted with the conventional generation system model to evaluate the reliability coefficients [86]. Milborrow had analyzed operating cost, availability and reliability of new and old machines in Germany [87]. Chands et al. had studied the expert-based maintenance methodology. It has the potential to improve the reliability of systems, besides the conventional monitoring function [88]. Denson analyzed the failure causes for electronic systems and factors contributing to failure cause parts [89]. The development of a structural safety assessment program with emphasis on wind effects had been described by Chen et al. and the traditional reliability index had been used in his studies and presented difficulties in the development of a program for estimating component probability of failure values [90].

7. Problems associated with wind turbines

Wind turbines components are subjected to various problems. Some method used for reducing failure of wind turbine components had been reviewed in this paper.

Joselin et al. had suggested various steps to tackle the different faults of wind turbine systems [91]. Blom et al. presented fatigue problems and related optimal experience of the two prototypes [92]. Dasgupta et al. introduced the tutorial series on fatigue failure mechanism and damage models. The specific failure mechanism depends on material or structural defect, damage induced during manufacture and assembly and on conditions during storage and field use [93]. Ramsamooj et al. presented a new analytical model for corrosion fatigue in an aggressive environment [94]. Zhiquan et al. used both experimental and theoretical methods to study the structural dynamic characteristics of rotor blades to avoid sympathetic vibration problem. The test revealed that the natural frequencies of flap-wise vibrations are lower than that of the torsional vibrations; flap-wise vibration is the main vibration of the rotor blade [95]. Makkonen et al. had proposed TURBICE model to prevent ice accretions on wind turbines [96].

Nair had presented the wind power has proven to be a potential source for generation of electricity with minimal environmental impact [97]. Stoudt et al. analyzed the influence of

a multilayered metallic coating on fatigue cracks nucleation and found that the multiplayer coating is responsible for retarding fatigue crack initiation and failure [98]. Chand et al. described asbestos free friction-lining material can be used for brake as well as other friction lining applications [99]. Lyntte presented the US operational experiences of wind farms due to the various causes such as problems of inadequate design, poor machine siting, and insufficient maintenance [100]. Ekanayake et al. surveyed a range of problems associated with the connection of an advanced static var. compensator (ASVC) to a wind farm network. It is shown that a high pass filter can effect a significant harmonic reduction for all harmonic frequencies above the designed tuned frequency [101].

Jacksan explained the greatest problem of down wind turbine noise [102]. Mohammed et al. had presented a stochastic and dynamic model that captures the uncertainties in the system load at the wind generator bus, capture noise due to wind effects for a grid-connected wind energy conversion system based on mathematical studies of stochastic process [103].

8. Wind turbine technology

Bhutt et al. reviewed the development of the technology of wind turbines and the various parameters related to the wind energy conversions [104]. Karaki et al. described the development of a general probabilistic model of an autonomous wind energy conversion system composed of several wind turbines connected to load and battery storage and to evaluate the energy purchased from or injected to the grid in the case of grid-connected systems [105]. Shikha et al. reviewed the research and development of technology of wind turbines and its impact on the cost of wind energy systems. Also the gap between the theoretical research and practical implementation had been analyzed and the problems associated with this have been outlined [106].

The cost and features of smaller machines had been compared by Parthan et al. with multi MW class wind turbine over 2 MW and there is a possibility of second-hand equipment in the 200–1000 kW range may be retrofitted with large unit size machines [107]. Eize de Vries considered the latest developments in wind turbine technology and looks at turbines that have come onto the market in recent months. He also reported on the state of the industry and future challenges that manufacturers will have to face [108].

8.1. Design

There are several aspects of the methods currently used for the design calculation of wind turbine performance and loading. The different types of analysis and methods for the design of wind turbine systems have been reviewed in this literature in a detailed manner.

According to Thomas and Urquhart, at present, both the horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) designs are very efficient, however both are being rigorously tested and improved [109]. Solero et al. had presented the design and testing of 5 kW direct-drive wind generator pilot plant being developed for stand-alone systems installed in extremely cold climates [110]. In professional practice throughout the world, design wind loads for a vast majority of structures have been evaluated by Singh on the basis of wind load provisions specified in standards and codes [111]. Chedid and Rahman performed a deterministic analysis to obtain optimal design for hybrid wind-solar power systems [112].

Ernesto et al. had developed a multi-objective optimization method for the design of HAWTs, based on the coupling of an aerodynamic model implementing the blade element theory and evolutionary algorithm [113]. Somasekhar et al. presented a methodology for the system design, selection of wind farm site and wind electric generator based on technical and economical analysis [114]. Quarton suggested the approach to wind turbine design has been transformed to the point where sophisticated computer-based analysis is now performed routinely throughout the industry. The increased power and memory of computers, coupled with the possibilities for extremely user-friendly software environments, allowed the wind turbine designer to undertake sophisticated design calculations in a straightforward and convenient manner [115]. Tempel et al. had described the large mass design of wind turbines would drive up cost. But by reducing the mass the cost effective turbine can be designed. To design a cost effective flexible system thorough understanding of the dynamics is essential [116].

8.2. Loads

As part of the design process, a wind turbine must be analyzed for aerodynamic loads, gravitational loads, inertia loads and operational loads it will experience during its design life. Researchers had developed various mathematical models for the calculation of structural loads and material stresses. A brief review of these mathematical models has been presented here.

Manuel et al. continued the work of Veers and Winterstein using probabilistic methods and parametric models based on uncertainty analysis was also performed. The effect of varying turbulence levels on long-term loads extrapolation techniques was examined using a joint probability density function of both mean wind speed and turbulence level for loads calculations [117]. Fitzwater and Winterstein examined the effect of statistical uncertainty dependent on the type of data used in these extrapolation methods [118]. Bierbooms had applied a probabilistic method to determine the extreme response of pitch regulated wind turbine caused by wind speed gusts. The proposed more accurate description of extreme loading will enable wind turbine manufacturers to build more reliable and optimized wind turbine [119]. Cluster analysis technique was used by Gomez-Munoz and Porta-Gandara during 2002 to find the local wind patterns for modeling renewable energy systems, which strongly depends on wind load [120].

A follow-up study by Ronold and Larsen, as well as Madsen et al. showed that these techniques could be used for ultimate load extrapolation and discovered that the statistics of the extremes more closely followed Gumbel-based distributions, as opposed to Weibull models commonly used for fatigue loading [121,122]. Mejia et al. described a positive regulator for the angular velocity of small wind turbines. This regulator reduced gyroscopic loads was easy to adjust and could be manufactured in smaller sizes and was much stronger than conventional vane used in small wind machine [123]. Veers and Winterstein studied the use of moments for predicting long-term fatigue loading and also introduced a nonlinear parametric model which was useful for extrapolating from limited data sets [124].

Ronold et al. had published a complete analysis of the uncertainty in a wind turbine blade fatigue life calculation. They used a parametric definition of the fatigue loads, matching the first three moments of the wind turbine cycle loading distribution to a quadratic (transformed by a squaring operation) Weibull distribution and also studied

calibration of partial safety factors [125]. Veers et al. had presented a methodology for using measured or simulated loads to produce a long-term fatigue-load spectrum at specified environmental conditions and at desired confidence levels [126]. Cheng et al. had considered extreme gust during the design process of the wind turbine with a rated power of 3 MW and used different distribution types, namely Rayleigh, Weibull and Gumbel distributions to provide a rational approach to determine the extreme gust response [127].

Verheij had developed a Gust Model for the design of large wind turbines and he explained the various wind loads and it causes [128]. Saranyasoontorn et al. investigated the influence of turbulence conditions on the design loads for wind turbine using inverse reliability technique and suggested that the inverse first-order reliability method in an efficient and accurate technique of predicting extreme loads and found that the higher relative turbulence at the onshore site leads to larger blade bending design loads than at the offshore site [129]. Dahlberg et al. described the results and conclusions drawn from measurements of structural loads in a wind turbine operating in a windfarm. The study showed that operation in a wake gives an increase in blade load variation [130]. LeRoy et al. had presented a methodology for proceeding from the short-term observation of extremes to the long-run load distribution of these extreme events, for both flap and edge loading in both operating and parked with turbine conditions [131]. Stol and Mark calculated aerodynamic loads by aerodynamic subroutines at prescribed elements along each blade length, using blade-element theory [132].

8.3. Blade

The development of special purpose aerofoil for HAWT began in 1984. New aerofoils have been developed to meet the specific demands of wind turbine. This has resulted in a greater efficiency of energy capture. Many researchers had developed different techniques for design, testing, fatigue strength analysis of wind turbine blades have been reviewed in the following literature.

Padgetl had developed a multiplicative damage model for strength of fibrous composite materials. This new model is needed to describe the failure of strength of these materials [133]. A simple micro-mechanical modeling procedure for evaluating fatigue strength unidirectional fibers composite had been described by Huang. It was expected that the present modeling approach is applicable to the fatigue analysis of laminated composites including in-phase and out of phase thermal-mechanical fatigue problems [134]. Fuglsang et al. had presented design and verification of the RISO-131 aerofoil family for wind turbines. High design lift coefficient of airfoils allowed the design of slender blades of wind turbine. Slender blades reduced both fatigue and extreme loads [135]. Dutta et al. studied the early airfoils, which were based on readily available aviation data and exhibited low lift-to-drag ratio with moderate power coefficient of the rotor. Modern blade evolved to its present shape through specific development effort, has achieved higher lift-to-drag ratio and increased power coefficient of about 0.5, and increase by about 20% [136].

A computerized method has been developed by Bir to aid preliminary design of composite wind turbine blades. The method allows for arbitrary specification of the chord, twist, and aerofoil geometry along the blade and an arbitrary number of shear webs [137]. Migliore et al. had conducted aeroaccoustic tests of seven aerofoils in wind tunnel. The test revealed that the trailing edge noise was dominant in clean tunnel flow and the leading edge noise was dominant in turbulent flow for all airfoils [138].

Hans van Leeuwen et al. had done two different sets of tests for comparing fatigue strength from full-scale blade tests with coupon-based predictions. One set of tests aimed at failing in the prismatic outboard section of the blade in the present glass fiber material. The other aimed at failing in the geometrically complicated root section of the blade where failure of the bounding line, collapse of the spar or other mechanisms can be observed [139].

Larwood and Musial of National Renewable Energy Laboratory (NREL) conducted single and two-axis fatigue tests on two Nedwind 12-m wind turbine blades and observed that the onset of visible damage occurred in the single-axis test [140]. Joosse et al. had investigated a cost-effective application of carbon fibers in wind turbine rotor blades. Fatigue strength for the stud joint increased by 20% when a limited number of carbon fiber layers were applied and the total costs of the turbine can be decreased by 4–5% when a carbon fiber spar is used in the blade [141]. Van Delft et al. presented the fatigue test of a full-scale rotor blade of the WPS 30 wind turbine and also developed a computer program to calculate the stress spectrum and fatigue strength in the blade. The test revealed the blade showing an ultimate load capacity 2.8 times the required strength [142]. Rumsey performed a test on a wind turbine blade was a fatigue test where a cycle loads was applied to the wind turbine blade until the blade fails. For this test, the wind turbine blade failed when blade mounting stub insert #12, pulled out of the root section of the blade [143].

Joosse et al. had conducted an acoustic emission monitoring of small wind turbine blades certification tests. The test revealed an audible cracking sound from the blade and identified the damage area of failure [144]. Rumsey et al. used one of the diagnostic techniques during a static test is acoustic emission (AE) nondestructive testing (NDT). A distributed and controlled static load is applied to the blade using a four-point Whiffle-tree arrangement. Step load increase and hold sequence is repeated until the wind turbine blade breaks [145].

Malayappan et al. had described the design of wind turbine blade and an analysis of wind turbine tower using finite element analysis [146]. Griffin et al. evaluated blade designs on the basis of power performance, weight, static strength in flap-wise bending, fatigue life in edgewise bending, and tip deflection under design loads [147]. Sutherland et al. had evaluated the effect of mean stress on damage of wind turbine blades. The damage analysis of wind turbine blades requires a detailed description of the fatigue load spectra and the fatigue behavior of blade material [148]. Johann et al. had presented the load spectrum of all critical positions on the wind turbine and designed each component and construction or welding detail and also carried out static and dynamic fatigue tests. As a result of the test it was found that the tested failure wind speed was 130 m/s, the desirable survival wind speed was 75 m/s [149].

Coupon tests with the variable-amplitude standard loading sequences for wind turbines known as WISPER and WISPERX. An alternative fatigue lifetime prediction formulations for variable-amplitude loading of wind turbine blades had been proposed by Nijssen et al. [150]. The difference between WISPER and WISPERX test for wind turbine blades was not predicted by van Delft et al. [151]. Thiringer et al. had analyzed the periodic power pulsations from three-bladed wind turbines and also investigated the influence of wind shear, wind speed, turbulence intensity, and rotor position and tower oscillation [152]. Kathleen O'Dell investigated new materials like carbon or glass-carbon hybrids, new manufacturing processes to produce blades for larger machines without increasing costs,

to improve fiber alignment and compaction, and to increase strength, reliability and performance [153]. Blackford given theory of wind turbine blade, blade designs procedure and blade construction [154]. James and James had suggested that a three-bladed rotor has a steady motion and is visually the most acceptable one [155].

Friedmann had reviewed recent research on aeroelastic and structural dynamic aspects of large horizontal-axis wind turbines and also discussed the various effects such as gravity loads, atmospheric gradient wind, tower shadow, moderate deflections, constant-power mode of operation and off-design operation [156]. Darris et al. analyzed the importance of load phase angle variations on fatigue damage using fatigue aerodynamics structures and turbulences (FAST) dynamics model and it had been observed that variable phase angle fatigue testing can influence the distribution of damage around the blade profile [157]. Fingersh conducted Unsteady Aerodynamics experiment horizontal axis wind turbine installed in the NASA Ames $80' \times 120'$ wind tunnel. When the turbine is at a yaw angle relative to the wind, the helical tip vortex bounding the wake is skewed. Here the rotor rotates at 72 rpm in a wind of 7 m/s [158].

Sorensen et al. analyzed drag distribution of the wind turbine blades parked at 90° to the oncoming flow. It indicates that a tip effect produces increased drag near the end of the blades. The drag also depends on the tapering and twisting of the blades, the rounded leading edges and the airfoil chamber [159]. Ostowari et al. investigated untwisted blade with NACA 44XX airfoils [160,161]. Dahlberg et al. investigated parking load on a 2.4 m wind turbines blade in a wind tunnel [162].

8.4. Gearbox

The gearbox was a source of failures and defects in many wind turbines. The design and various problems of WEGs have been reviewed in this literature.

Lin et al. presented procedures for designing compact spur gear sets with the objective of minimizing the gear size. Various dynamic rating factors were investigated and evaluated. Tooth bending failure at the root is a major concern in gear design. If the bending stress exceeds the fatigue strength, the gear tooth has a high probability of failure [163]. Shanmugam presented that for the year 2003, gearbox problem tops the list of failures recorded in Denmark and in Germany according to Windstats [164]. Sivakumar experienced that the wind power generation supported by a scientific inventory management had produced excellent results for Ramco Wind Farm. This is all the more so with respect to gearboxes which tend to break down after 23000/30000 h of operation [165]. Vasudevan et al. studied the critical parameters for fatigue damage of structural components under a variety of loading and environmental conditions. These defects initiate cracks that grow with time, finally leading to the failure of the components and suggested two mechanisms for fatigue damage control [166].

8.5. Generator

The electrical system of the wind turbine includes all components for converting mechanical energy into electrical power. A brief review of the generator has been illustrated here.

Tripathy investigated the possibility of using self-excited induction generator for wind power generation and reported normally designed three-phase squirrel cage induction

motor can be used as a wind turbine driven self-excited induction generator for supplying the load demand [167]. Haack used a computer-operated simulation model, which incorporates wind speeds, residential electricity demands and parameters from generator, inverter and storage components to determine the amount of energy from a wind-energy conversion system [168]. Daqiang et al. established an improved transient simulation of salient pole synchronous generators with internal and ground faults in the stator winding using the multiloop circuit method [169]. Muljadi et al. reported an innovative conversion system that converts energy from a variable-frequency wind-powered induction generator to a fixed frequency load. Using only a six-switch DC link CPRWM inverter and a zero sequence filter, energy is provided to a single-phase load at a fixed 60 Hz frequency [170]. Datta et al. had done a comparative study with constant speed system with cage rotor induction machine, variable speed system with cage rotor induction machine, slip ring induction machine and concluded that a variable speed system using wound rotor induction machine is superior [171].

Agarwal et al. had done an analytical investigation of a self-excited induction generator and also developed an algorithm to compute the excitation requirement of the machine for a wide range of speeds keeping the terminal voltage constant at desired value [172]. The configuration of short-shunt self-excited induction generator feeding induction motor loads suffers from excessive transistors during startup of motor load under no load and unstable operation. Singh et al. proposed damping resistors across series capacitors to damp out the starting transients and for the stable operation [173]. Chalmers et al. proposed an axial-flux permanent-magnet generator for a gearless, variable-speed wind energy system [174]. Akhmator et al. had proposed variable-speed wind turbine with multipole synchronous permanent magnet generators for large offshore wind farms [175]. Popescu et al. presented a detailed analysis of the asynchronous torque components for a single-phase capacitor-start, capacitor-run permanent magnet motor [176]. Alan et al. had presented asymmetry and imbalance can lead to torque ripple, current wave form shaping can be used to mitigate torque ripple and reduce RMS current in permanent magnet synchronous drive [177].

Douglas et al. had shown that broken bars could be detected by the decomposition of the startup current transient in motors as well as in wind generator [178]. Siddique et al. reviewed various stator faults, their causes, detection parameters/techniques, and latest trends in the condition monitoring technology [179]. In permanent magnet, synchronous iron losses form a larger portion of the total losses than in induction machines. Chris et al. considered the minimization of iron losses of permanent magnet synchronous machines through the proper design of magnet and slots and through the choice of the poles [180]. Bhagwatikar and Gandhare's measurement and study showed that the harmonic distortion in voltage is ranging from 2.5% to 9.5% in case of induction-type wind generators and 6–12% in variable speed generators. It is also seen that the wind turbines also generates even harmonics and interharmonics. No load loss greatly increases under the condition of harmonic distortion [181]. Venkatesh demonstrated a well-designed reactive power compensation system and harmonic filters for energy conservation in distribution system of wind turbine [182]. There are three main elements that contribute to reactive power flow in a wind farm. Transformer and inductive generator contribute inductive reactive power and capacitor contributes to captive reactive power. Venkatesh had analyzed some aspects of reactive power management in wind farms [183].

8.6. Transformer

Transformer is an integrated part in the power system. In the wind power projects, the transformer is used to interlink the turbine generator and the utility grid.

Bhawatikar et al. recommended that the use of high-efficiency transformers made up of amorphous metal to reduce electrical losses [184]. Ellis et al. had presented the scope for improving the efficiency of a transformer can arise in a number of ways. The size of a transformer being installed in the network and the way in which they are loaded can greatly increase savings. The transformers are at maximum efficiency when approximately 50% loaded [185].

9. Grid connection

The different techniques and methods for the grid-related problems of WEGs have been reviewed in this literature.

Tande et al. studied the demonstration of the utilization of modern wind turbine technology and automatic generation control schemes to allow operation of large wind farms in weak grids [186]. Pareto analysis had been done by Iniyan et al. to analyze the grid-related problems of wind turbine generators. The system would supply reliable power when there is no grid failure [187]. Akhmator investigated the model of variable speed pitch controlled wind turbines, with doubly fed induction generation model with the back-to-back converters and presented that the main problems at grid disturbance are risks of over currents in the generators and the converter, and over voltage in the DC-link [188]. Akhmator discussed simulation model on large wind farm, when subjected to a short-circuit fault, the wind turbines show current response at the grid fault. He has suggested a model for voltage stability investigation of large power systems [189].

Venkatesh presented that the poor quality of grid affects wind electric generator's performance and wind generators create power quality problems. Due to this, the operational efficiency of the wind farm gets reduced and also results in poor grid power quality and increased losses for the utilities and other consumers [190]. Chen and Spooner discussed grid power quality with variable speed wind turbine for studying the voltage fluctuation and harmonic distortion in a network to which variable speed wind turbines are connected [191]. Kanellos et al. analyzed the repercussions from the connection of wind parks on the operation of weak electric distribution systems, based on simulation results and confirmed the possible increase in the installed capacity of the wind park over the fixed-speed mode, maintaining the same power quality standards, is estimated [192]. Thiringer studied power quality measurements performed on a low-voltage grid equipped with two wind turbines and it has been noted that the grid short circuit power and the X/R ratio of the grid have a great influence on the power quality impact from wind turbine [193].

The electrical limiting factors for installation of wind turbine had been used by Stefan et al. to determine which types of power quality problems that will dominate when wind turbine are installed in weak grids [194]. Various factors affecting wind power, siting of wind electric generator and selection of equipments and method of grid connections of wind electric generators and problems associated with grid inter-connections had been discussed by Bansal et al. [195]. Giuseppe et al. compared variable speed wind turbine and constant speed wind turbine. Variable speed improves the dynamic behavior of the turbine,

thereby alleviating the stresses on the mechanical construction. A major drawback when using grid-connected VSCs is their sensitiveness to grid disturbances [196].

10. Control system

The controller is provided with display unit for the display of instantaneous position of generation, different temperature of generator, rotor rpm and generator rpm, different grid parameters active and reactive consumption, etc. It also has data storage capacity and memory to keep records of different faults. A brief review of these control systems have been presented here.

One of the main goals of wind turbine control is to increase power production and reduce loads with a minimum number of control inputs required for turbine measurement. Hinrichren used classical control design methods such as proportional integral, to design controllers to regulate power [197]. Mufti et al. discussed the control of a standalone power system comprised of a pitch controlled wind turbines and two-diesel unit. The design of the various control schemes ensures that the system performs well under both wind and load disturbances [198]. Hernan et al. addressed the problem of output power regulation of fixed-pitch variable speed wind energy conversion systems. A dynamical variable structure controller was developed for power regulation of wind turbine systems [199]. Liebst describes the use of individual blade periodic pitch control to reduce the loads on the mod 0-A turbine caused by tower shadow, wind shear and gravity [200].

Hasen et al. presented an overall control method for variable speed pitch controlled wind turbines with doubly fed induction generators (DFID). They implemented a dynamic performance of grid connected wind turbine within realistic electrical grid models [201]. Walker and Jenkins studied that under active stall technique, the turbine blades, which are normally left at fixed position could change their pitch-angle during braking [202]. Yen Dam et al. introduced micro-electro-mechanical (MEM) translational tabs for active load control on aerodynamic surfaces such as wind turbine rotor blades. Results showed an increase in lift from baseline in the linear range of the lift curve being generated by these micro-scale devices [203]. Ezzeldin et al. had presented the modeling and controller design for a wind turbine induction generator unit. The mechanical power input was controlled using the blade pitch-angle. Both state and output feedback controllers are designed using MATLAB software to regulate the generator output. From the simulation results, the response of closed loop system exhibited a good damping and fast recovery under different types of large disturbances [204]. Stol and Balas designed controllers with periodic gains to regulate turbine speed and reduce loads for a two-bladed teetering hub machine [205]. Kojabadi et al. had done comparison of the measured torque with this demand torque, the shaft torque of the induction motor is regulated accordingly by controlling stator current demand and frequency demand of an inverter, which can improve the effectiveness, and efficiency of research and development in the wind energy conversion system [206]. Neris et al. had used an Insulated Gate Bi-polar Transistor (IGBT) inverter for both control of active and reactive power supplied to the grid and to reduce harmonic distortion [207]. A control strategy to improve the stability of a large wind farm using state reactive power compensator (STATCOM) and dynamic braking resistor (DBR) is proposed and investigated by Arulappan et al. The STATCOM supplies the reactive power demand of the wind farm dynamically in order to maintain the network voltage [208].

Ledesma proposed two-voltage control scheme for variable speed wind turbines with double fed induction generator [209]. Miller et al. showed a simple frequency control operated at constant V/Hz is capable of controlling the power flow of the system to match the maximum power coefficients of a wind turbine for standard operating ranges. If the applied voltage is kept directly proportional to the frequency, the current in the machine would remain constant at a given slip frequency [210]. Gavanidou et al. analyzed small autonomous systems and found that the wind energy penetration was limited, but it can be optimized if central control of WECs is used [211].

Kethryn et al. introduced new control methods to address significant power loss for standard region 2-control scheme for a variable speed wind turbine and resulted in an optimally tracking rotor control scheme which can improve upon the standard scheme by assisting the rotor speed in tracking wind speed fluctuations more rapidly [212]. Moriarty et al. had studied the scale and lag effects on control of aerodynamic power and loads on a HAWT rotor. It was discovered that the power fluctuations are reduced by one half or more when aerodynamic loads are actively controlled [213]. Stol applied disturbance tracking control theory to the design of a torque controller to optimize energy capture under the influence of persistent wind disturbances. Results indicate a 24% reduction in blade fatigue damage using the proposed controller. Tower-based fatigue damage was shown to decrease significantly when using active pitch [214]. Johnson described the theory of disturbance accommodating controllers in advances in control and dynamic systems for accounting persistent with wind disturbances [215].

Alan et al. applied modern state space control design methods to regulate turbine speed and enhance damping. The controls approach is based on the Disturbance Accommodating control method and provides accountability for wind speed disturbance [216]. Barton et al. included a power system stabilizer in 2 MW wind turbine generator to add damping to the drive train mode [217]. Wright and Balas described various flexible modes of a turbine were stabilized by control designs using rotor collective pitch [218]. The control structure of a wind energy conversion is analyzed by Bouscayrol et al. and discussed simplification of the control structure in order to reduce the global cost [219]. Conner and Leithhead had sought to improve on the standard control by using various controls techniques and investigated the use of different measures of torque in the tracking error [220].

11. Economics of wind turbine system

Wind generator costs are heavily linked to the characteristics of a wind resources in a specific location. Cost effectiveness of future wind turbines depend more on having dynamic and compliant design than on increased size. Hossain et al. had achieved the most profitable wind electric generation by the identification of the most cost effective rating of wind electric converters for the candidate sites, by minimizing costs involved in developing the site and by reducing the down time of the machine [221].

12. Application of wind turbine converters

Spring Field had explained about the use of rotational energy produced by the rotation of blades to operate a mechanical device such as a water pump or to produce electricity by means of generator [222]. GaraRa et al. described the various applications of wind turbine

such as desalination processor suitable for coupling to wind turbines are reverse osmosis (RO), mechanical vapour compression (MVC) and electro-dialysis (ED) [223]. Sidding had compared the two conventional pumping methods and revealed the wind turbine is the feasible pumping prime mover at average wind speed exceeding 3 m/s [224]. Thomas et al. invented wind energy-capturing device for moving vehicles. The electrical energy may be stored in a battery system and used to drive the motor of an electric vehicle (or) hybrid electric vehicle [225].

13. Conclusion

Remarkable advances in wind turbine design have been possible due to developments in modern technology. The advanced wind turbine technologies have been reviewed as follows.

- The factors such as selection of site, height, choice of wind generators, wind velocity, wind power potential have been considered as an objective function of probabilistic models. These mathematical models are used to determine the energy output of the wind turbine system.
- Weibull, Rayleigh distribution and Markov chain model were found suitable to predict wind speed data for the site. Selection of windy site for wind power generation requires meteorological data for installation of wind generator.
- Experimental and theoretical methods are used to analyze vibration problems of wind turbines. Rain flow counting, a linear Goodman fit and Miner summation are used for lifetime prediction of wind turbine blades. The aeroelastic and structural dynamic aspect helps in understanding various loads used for design and fatigue damage.
- Aeroaccoustic tests are used to find noise in the aerofoil.
- Computer-based supervisory control is used to identify operating characteristics of wind turbines.
- Static reactive power compensator is used to improve stability of large wind farms. Parato analysis and simulation models are used to analyze grid-related problems.
- Wind field modeling is an important part of a structural analysis of wind turbines.
- In aerodynamic modeling blade element moment theory is used for calculation of aerodynamic forces acting on the rotor blade.
- Control system modeling is used to keep the operating parameters of the wind turbine within the specified limit. These developments and growing trends towards wind energy signal is a promising future for the wind energy industry. With this improved technology wind turbine can be designed for its optimum power production at less cost.

This paper will be useful for the wind turbine manufacturer, generating members and decision makers. It is also concluded that less number of authors had been worked on reliability evaluation of wind turbine systems. New research techniques on reliability evaluation will be the bright future in the wind turbine technology.

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